

Transverse Mode Dynamics and Ultrafast Modulation of Vertical-Cavity Surface-Emitting Lasers

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ABSTRACT

We show that multiple transverse mode dynamics of VCSELs can be utilized to generate ultrafast intensity modulation at a frequency over 100 GHz, much higher than the relaxation oscillation frequency. Such multimode beating can be greatly enhanced by taking laser output from part of the output facet.

High frequency modulation of semiconductor lasers is important for quite a number of applications in optical communications, and in microwave photonics.¹⁻³ Due to the long carrier recombination time in typical semiconductor devices used for optoelectronic applications, direct modulation beyond 10 GHz seems to be quite difficult. On the other hand, ultrafast semiconductor sources for narrow band modulation based on a Q-switching type of technique or multi-longitudinal mode-lockings have been realized in edge-emitting lasers (EELs) with multi-section design. Such methods have produced high modulation bandwidth beyond the limit achievable by direct current modulation. Due to the complex multi-section design, such techniques are difficult to be reproduced for a typical VCSEL configuration. Since VCSELs have many intrinsic advantages over edge emitters, such as easy 2D realization and less divergent and circular beam shapes, high frequency modulation of VCSELs is of clear importance.

Vertical-cavity surface emitting lasers are known to operate in multiple transverse modes even at a moderate pumping level.^{4,5} However, when the total output is collected and used, the multimode beating signals will diminish due to spatial averaging. This is especially true for strongly index guided VCSELs, such

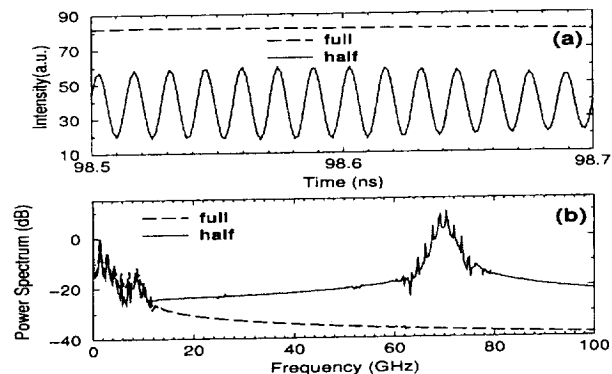


Figure 1. Time evolution (a) of the laser intensity integrated over the entire device output facet (dashed line) and over half of the output facet (solid line). Figure (b) represents the corresponding Fourier spectra. The device is gain and index-guided with a diameter of 10 μm and operated slight above threshold under DC pumping.

as oxide-confined devices where spatial averages completely wipe out the mode beating signal.⁵ In this paper, we make a detailed study of strongly index-guided VCSELs and compare the spectral response of the total near field with that of near-field collected from half of the output facet. We show that a strong spectral response at the mode beating frequency appears for the partial near field, while no response at this frequency for the total near-field shows up. We suggest the use of this scheme to generate high frequency modulated VCSEL sources for narrow band applications.

To demonstrate the suggested scheme, we conducted a detailed numerical simulation. The model has been described in our recent paper.⁵ The essence of the model is solving a set of partial differential equations for

complex laser field amplitude, optical polarization, and carrier density in the space and time domain without assuming the number and type of transverse modes. We also take into account the modal frequency dependence of the optical gain, so that different transverse modes have slightly different gain depending on their spectral positions in the gain spectrum. Since a direct space-time domain finite-difference method is used, the simulation allows easy specification of size and shape of the active region as well as index-guiding strength and size. In the following simulation, we use a one-wavelength cavity for a 980 nm VCSEL. We choose two device sizes for both gain and index guidings. An effective index step of 0.05 was chosen to represent the index guiding in a typical oxide confined VCSEL.

Figure 1(a) shows temporal waveforms for the total output intensity (dashed line) and for the intensity collected from half of the output facet (solid line). The laser has a diameter of 10 micrometers. We see clearly that there is no appreciable variation of the total intensity on the time scale shown in the figure. But the solid line shows a very regular oscillation at a frequency around 70 GHz. The variation in the amplitude on this time scale arises from a slower change related to the relaxation oscillation. In figure 1(b) we show the corresponding power spectra for the total output (dashed line) and for the partial output with half of output aperture (solid line). The much stronger response around 70 GHz is related to the mode beating giving rise to the periodic waveform shown in Fig.1(a), while the lower frequency features within 10 GHz are related to the relaxation oscillation. To increase the modulation frequency, we decrease the device size to 7.5 micrometers in diameter. The corresponding figures are shown in Fig.2, where we see that a modulation frequency of 130GHz is achieved.

In summary, we have studied multiple trans-

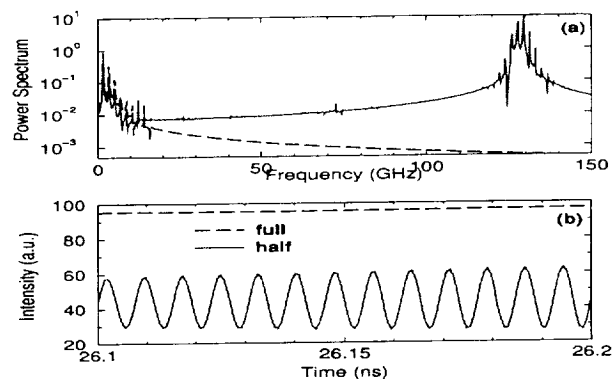


Figure 2. Time evolution (b) of the laser intensity integrated over half of the output facet. Figure (a) represents the windowed-Fourier transform of the time series in different evolution stages (time windows) to reveal spectrum features in different time windows. Device parameters and operating conditions are the same as in Fig. 1

verse mode behavior in an index guided VCSEL. We compared the total output and the partial output from half of the output facet with respect to their temporal waveform and spectral responses. The partial output carries a strong multiple mode beating signal and can be used for applications that require ultrafast narrow band modulation. We also studied the effects of an AC modulation on the dynamic response of VCSELs. The result for smaller devices with higher modulation frequencies will also be presented.

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Outline

- Introduction (application and generation)
- Model and Equations
- Coupled VCSELs
- Multi-Transverse Mode Dynamics
- Modulation of Multimode VCSELs
- Extension of Bandwidth
- Conclusion

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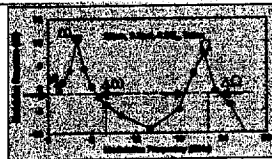


Introduction: Application

Ultrafast: $\Omega \gg \omega_{\text{ro}}$

Narrow Band: $\Delta\Omega \ll \Omega$

(digital application: $\omega_{\text{ro}} \sim \Delta\omega$)



- Microwave, millimeter-wave photonics
- Narrow-band communications
- All-optical clock generation and recovery
- Digital communication, if bandwidth $\Delta\Omega$ expanded

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Introduction: Generation

- Modulation of mode-locked (-coupled) lasers at 100GHz (theory, Lau 1988,1990)
- Resonant enhancement by feedback (experiment, Lau and Yariv 1985) or by external cavity (Nagarajan et al 1993)
- Push-pull modulated DFB lasers (theory, Marceac et al 1994)
- Detuned DBR lasers (theory, Felste 1998)
- 2-Section DBR lasers (theory and experiment, Kjebo et al 1997, Morthier et al 2000)
- Coupled twin-stripe edge-emitters (PW, Wednesday)

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Common features:

- Second resonance in addition to the RO oscillation either through external cavity, feedback or multimode beating
- Edge emitters of complex structures: multi-section DBR or DFB lasers or needing external cavity or feedback

Proposal: VCSELs

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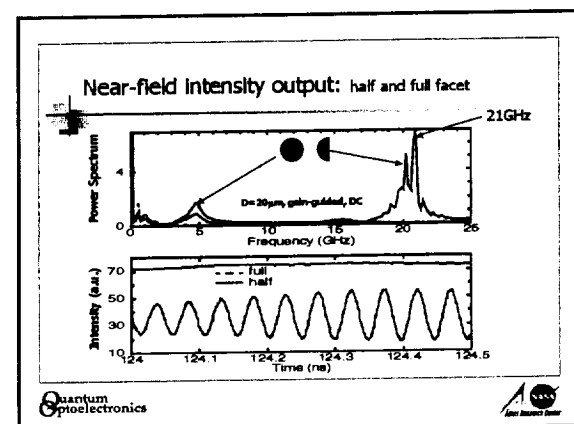
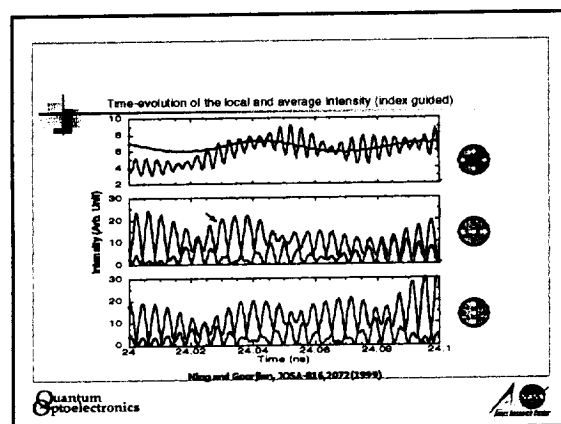
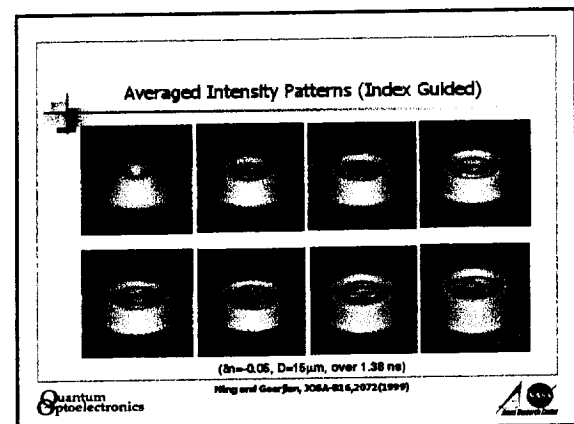
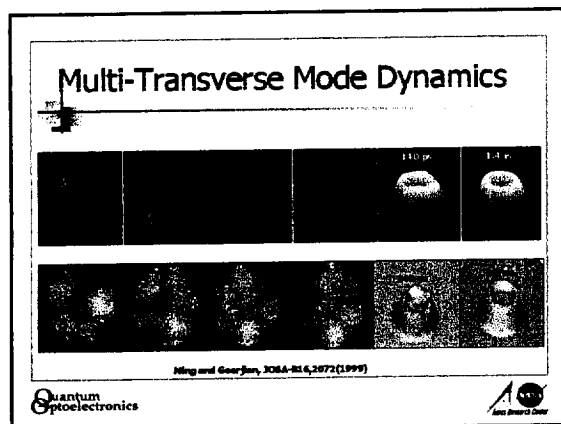
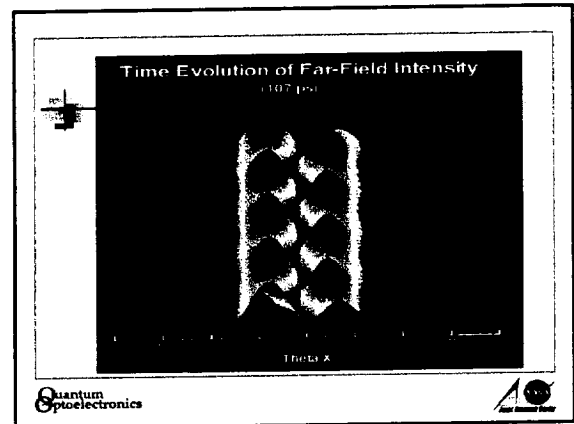
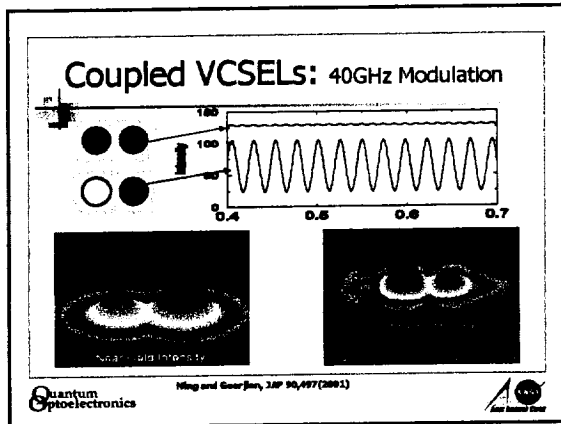
Model and Equations

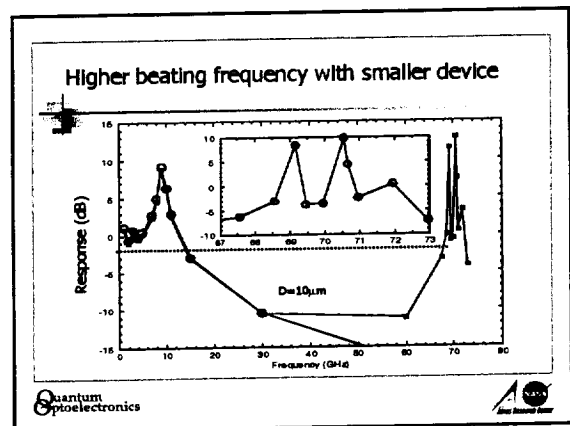
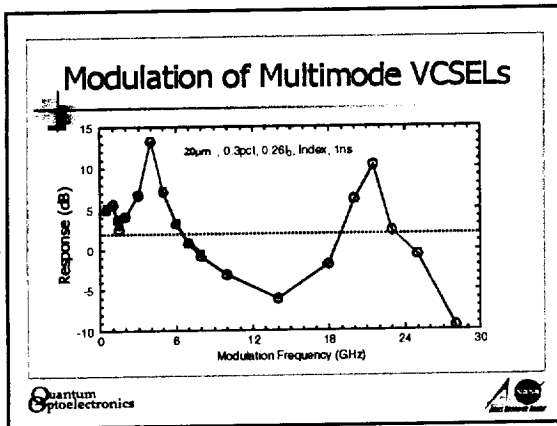
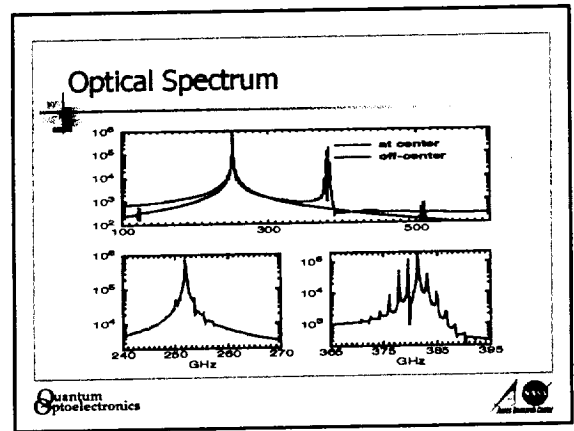
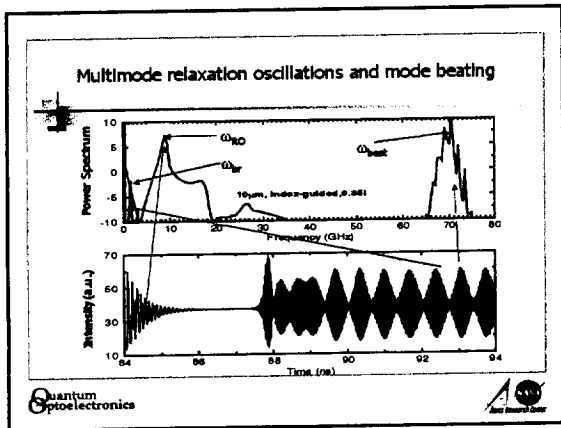
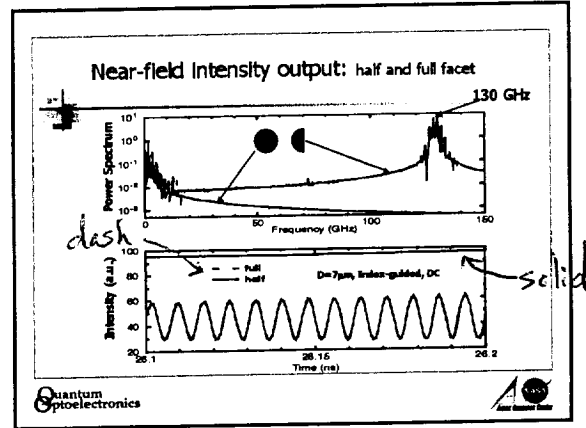
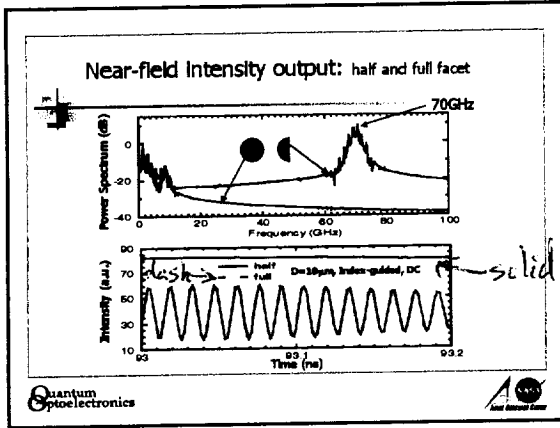
$$\begin{aligned} \frac{n_s}{c} \frac{\partial E}{\partial t} &= \frac{i}{2K} \nabla^2 E - \kappa E + \frac{iK\Gamma}{2\epsilon_0 \epsilon_b} P + \frac{i\delta n(x,y)}{n_s} KE \\ \frac{\partial N}{\partial t} &= \nabla D \nabla N - \gamma N + \eta \frac{J(x,y,t)}{e} + \frac{iL\Gamma}{8\hbar} (P^* E - P E^*) \\ \frac{dP_j}{dt} &= \{-\Gamma_j(N) + i[\delta_0 - \delta_j(N)]\} P_j - i\epsilon_0 \epsilon_b A_j(N) E \\ (P &= P_0 + P_1 + \dots) \end{aligned}$$

(Mina, Brille, Melzer, 2006, 1997)

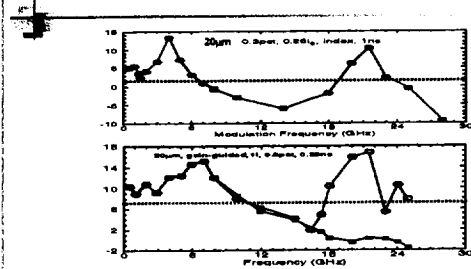
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Extension of Bandwidth



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Conclusion

- Multimode beating greatly enhanced by taking output from part (e.g., half) of output facet
- Simpler sources of microwave, millimeter wave of various frequencies generated by varying VCSEL diameter in a single multimode VCSEL or coupling of a few VCSELs
- Breathing frequency in multi-mode operation affects modulation response and bandwidth
- Optimizing RO frequency and mode beating frequency could potentially expand bandwidth suitable for wide band digital communication

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